GLOBAL TRANSMISSION COEFFICIENTS IN HAUSER–FESHBACH CALCULATIONS FOR ASTROPHYSICS

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Abstract

The current status of optical potentials employed in the prediction of thermonuclear reaction rates for astrophysics in the Hauser–Feshbach formalism is discussed. Special emphasis is put on α+nucleus potentials. Further experimental efforts are motivated.

1 Introduction

The investigation of explosive nuclear burning in astrophysical environments is a challenge for both theoretical and experimental nuclear physicists. Highly unstable nuclei are produced in such processes which again can be targets for subsequent reactions. Cross sections and astrophysical reaction rates for a large number of nuclei are required to perform complete network calculations which take into account all possible reaction links and do not postulate a priori simplifications.

The majority of reactions can be described in the framework of the statistical model (compound nucleus mechanism, Hauser–Feshbach approach, HF) [1], provided that the level density of the compound nucleus is sufficiently large in the contributing energy window [2]. In astrophysical applications usually different aspects are emphasized than in pure nuclear physics investigations. Many of the latter in this long and well established field were focused on specific reactions, where all or most "ingredients", like optical potentials for particle transmission coefficients, level densities, resonance energies and widths of giant resonances to be implemented in predicting E1 and M1 γ–transitions, were deduced from experiments. As long as the statistical model prerequisites are met, this will produce highly accurate cross sections. For the majority of nuclei in astrophysical applications such information is not available. The real challenge is thus not the well–established statistical model, but rather to

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provide all these necessary ingredients in as reliable a way as possible, also for nuclei where none of such information is available.

2 Transmission Coefficients

The final quantities entering the expression for the cross section in the statistical model [1] are the averaged transmission coefficients. They do not reflect a resonance behavior but rather describe absorption via an imaginary part in the (optical) nucleon–nucleus potential [3]. In astrophysics, usually reactions induced by light projectiles (neutrons, protons, α particles) are most important. Global optical potentials are quite well defined for neutrons and protons. It was shown [4, 5] that the best fit of s–wave neutron strength functions is obtained with the optical potential by [6], based on microscopic infinite nuclear matter calculations for a given density, applied with a local density approximation. It includes corrections of the imaginary part [7, 8]. A similar description is used for protons. Deformed nuclei are treated by an effective spherical potential of equal volume [5]. For a detailed description of the formalism used to calculate E1 and M1 γ–transmission coefficients and how to include width fluctuation corrections, see [2, 5] and references therein.

2.1 α+Nucleus Potentials

Currently, there are only few global parametrizations for optical α+nucleus potentials at astrophysical energies. Most global potentials are of the Saxon–Woods form, parametrized at energies above about 70 MeV, e.g. [9, 10]. The high Coloumb barrier makes a direct experimental approach very difficult at low energies. More recently, there were attempts to extend those parametrizations to energies below 70 MeV [11].

Early astrophysical statistical model calculations [12, 13] made use of simplified equivalent square well potentials and the black nucleus approximation. Improved calculations [14] employed a phenomenological Saxon–Woods potential [15], based on extensive data [16]. This potential is an energy– and mass–independent mean potential. However, especially at low energies the imaginary part of the potential should be highly energy–dependent.

Most recent experimental investigations [17, 18] found a systematic mass– and energy–dependence and were very successful in describing experimental scattering data, as well as bound and quasi–bound states and B(E2) values, with folding potentials [19]. Motivated by that description (a global parametrization is not given in [18]), the following global α+nucleus potential is

proposed. The real part $V = \lambda V_{\mathrm{f}}$ of the optical potential is calculated by a double–folding procedure:

$$V_{\mathrm{f}}(r) = \int\int \rho_{\mathrm{P}}(r_{\mathrm{P}})\, \rho_{\mathrm{T}}(r_{\mathrm{T}})\, v_{\mathrm{eff}}(E, \rho_{\mathrm{N}} = \rho_{\mathrm{P}} + \rho_{\mathrm{T}}, s = |\vec{r} + \vec{r_{\mathrm{P}}} - \vec{r_{\mathrm{T}}}|)\, d^3 r_{\mathrm{P}}\, d^3 r_{\mathrm{T}} \quad , \tag{1}$$

where ρ_{P}, ρ_{T} are the nuclear densities of projectile and target, respectively, and v_{eff} is the effective nucleon–nucleon interaction taken in the well–established DDM3Y parametrization [20]. The remaining strength parameter λ can be determined from the systematics [17] of the volume integral per interacting particle pair

$$J_R = \frac{1}{A_{\mathrm{P}} A_{\mathrm{T}}} \int V(r)\, d^3 r \quad . \tag{2}$$

Introducing a mass–dependence in addition to the energy–dependence, one can reproduce the behavior derived from the imaginary part by applying the dispersion relation [18], by the relation

$$J_R = \left\{ \begin{array}{ll} f(A) + 0.67 E_{\mathrm{c.m.}} & (E_{\mathrm{c.m.}} \leq 26) \\ {[0.011 f(A) - 2.847]}\, E_{\mathrm{c.m.}} - 1.277 f(A) + 626.591 & (26 < E_{\mathrm{c.m.}} < 120) \end{array} \right. , \tag{3}$$

with $f(A) = 311.0132 \exp\left(A_{\mathrm{T}}^{-2/3}\right)$ and $E_{\mathrm{c.m.}}$ given in MeV. Using Eqs. 2 and 3, the value of λ can be set.

The mass– and energy–dependence of the imaginary part is more crucial for the calculation of transmission coefficients. The volume integral of the imaginary part can be parametrized according to [21]:

$$J_I(E_{\mathrm{c.m.}}) = \left\{ \begin{array}{cl} 0 & \text{for } E_{\mathrm{c.m.}} \leq E_0 \\ J_0 \cdot \frac{(E_{\mathrm{c.m.}} - E_0)^2}{(E_{\mathrm{c.m.}} - E_0)^2 + \Delta^2} & \text{for } E_{\mathrm{c.m.}} > E_0 \end{array} \right. \quad , \tag{4}$$

where E_0 is the threshold energy for inelastic channels, J_0 is a saturation parameter and Δ the rise parameter.

As can be seen [18], the resulting volume integrals are quite diverse for different nuclei and a straight–forward mass–dependent parametrization is not possible. In Ref. [18], J_0 and Δ were fitted to experimental data. For a global parametrization, one has to include nuclear structure and deformation information into the fit. Having chosen the (probably energy–dependent) geometry parameters [11] (and appropriately modified them for deformed nuclei), the depth W of an imaginary Saxon–Woods potential can be determined with Eq. 4. At energies $E_{\mathrm{c.m.}} > 100$ MeV, the value of W should reach the saturation value [10]. This determines the parameter J_0. The threshold $E_0 = E_0(\rho)$

is given by the energy of the first excited state. The increase in the number of inelastic (competing) channels is described by Δ. As a first estimate, this can be related to the increase in the total number $n = n(\rho)$ of levels: $\Delta = f\,(dn/dE) = \alpha E_0 + \beta A^{2/3} + \gamma \ln{(dn/dE)}$. The functional dependence is found by comparison with experimental values for Δ [18]. Thus, microscopic and deformation effects are implicitly included via the level density $\rho = \rho(E)$.

With nuclear level densities $\rho(E)$ taken from [2], a good fit is obtained to the values given in [18], as well as for various (α,γ) and (n,α) data [22]. However, it has to be emphasized that the aim is to obtain a reasonable *global* potential, i.e. with a low *average* deviation from experiment. For specific reactions, such a potential might be improved by fine–tuning to a particular nucleus (e.g. [23, 24]) but will lose predictive power by that.

3 Conclusion

With the recent improvements of the level density treatment [2] and the α+nucleus potential, the two major remaining uncertainties in the existing global astrophysical reaction rate calculations have been attacked. The new descriptions will provide more reliable predictions of the low–energy cross sections of unstable nuclei.

Nevertheless, to check and further improve current parametrizations, not only of α+nucleus potentials but of all involved quantities, experimental data is needed. Especially investigations over a large mass range would prove useful to fill in gaps in the knowledge of the nuclear structure of many isotopes and to construct more powerful parameter systematics. Such investigations should include neutron– and proton–strength functions, as well as radiative widths, and charged particle scattering and reaction cross sections for *stable* and unstable isotopes. This information can be used to make future large–scale statistical model calculations even more accurate.

References

[1] W. Hauser and H. Feshbach, Phys. Rev. **87** (1952) 366

[2] T. Rauscher, F.-K. Thielemann, and K.-L. Kratz, Phys. Rev. C **56** (1997) 1613

[3] C. Mahaux, H.A. Weidenmüller, Ann. Rev. Part. Nucl. Sci. **29** (1979) 1

[4] F.-K. Thielemann, J. Metzinger, and H.V. Klapdor, Z. Phys. A **309** (1983) 301

[5] J.J. Cowan, F.-K. Thielemann, J.W. Truran, Phys. Rep. **208** (1991) 267

[6] J.P. Jeukenne, A. Lejeune and C. Mahaux, Phys. Rev. C **16** (1977) 80

[7] S. Fantoni, B.L. Friman and V.R. Pandharipande, Phys. Rev. Lett. **48** (1981) 1089

[8] C. Mahaux, Phys. Rev. C **82** (1982) 1848

[9] P.P. Singh and P. Schwandt, Nukleonika **21** (1976) 451

[10] M. Nolte, H. Machner and J. Bojowald, Phys. Rev. C **36** (1987) 1312

[11] V. Avrigeanu, P.E. Hodgson, M. Avrigeanu, Phys. Rev. C **49** (1994) 2136

[12] M. Arnould, A&A **19** (1972) 92

[13] S.E. Woosley, W.A. Fowler, J.A. Holmes, and B.A. Zimmerman, At. Data Nucl. Data Tables **22** (1978) 371

[14] F.-K. Thielemann, M. Arnould and J.W. Truran, in *Advances in Nuclear Astrophysics*, ed. E. Vangioni–Flam, Gif sur Yvette 1987, Editions Frontière, p. 525

[15] F.M. Mann, 1978, Hanford Engineering, report HEDL-TME 78–83

[16] L. McFadden and G.R. Satchler, Nucl. Phys. **84** (1966) 177

[17] P. Mohr, H. Abele, U. Atzrott, G. Staudt, R. Bieber, K. Grün, H. Oberhummer, T. Rauscher, and E. Somorjai, in *Proc. Europ. Workshop on Heavy Element Nucleosynthesis*, eds. E. Somorjai and Zs. Fülöp, Institute of Nuclear Research, Debrecen 1994, p. 176

[18] U. Atzrott, P. Mohr, H. Abele, C. Hillenmayer, and G. Staudt, Phys. Rev. C **53** (1996) 1336

[19] G.R. Satchler and W.G. Love, Phys. Rep. **55** (1979) 183

[20] A.M. Kobos, B.A. Brown, R. Lindsay, and R. Satchler, Nucl. Phys. **A425** (1984) 205

[21] G.E. Brown and M. Rho, Nucl. Phys. **A372** (1981) 397

[22] V. Hansper, private communication

[23] P. Mohr, T. Rauscher, H. Oberhummer, Z. Máté, Zs. Fülöp, E. Somorjai, M. Jaeger, and G. Staudt, Phys. Rev. C **55** (1997) 1523

[24] E. Somorjai, Zs. Fülöp, Á.Z. Kiss, C.E. Rolfs, H.P. Trautvetter, U. Greife, M. Junker, S. Goriely, M. Arnould, M. Rayet, T. Rauscher, and H. Oberhummer, A&A, in press